Proceedings of the 2003 IEEE
International Conference on Robotics & Automation
Taipei, Taiwan, September 14-19, 2003

Exoskeleton for Human Upper-Limb Motion Support

Kazuo Kiguchi[*1], Takakazu Tanaka[*1], Keigo Watanabe[*1], Toshio Fukuda[*2]

*1: Dept. of Advanced Systems Control Eng.
Saga University
1 Honjomachi,
Saga-shi, Saga 840-8502, Japan
E-mail: kiguchi@ieee.org

*2: Dept. of Microsystem Engineering
Nagoya University
1 Furo-cho, Chikusa-ku,
Nagoya 464-8603, Japan
E-mail: fukuda@mein.nagoya-u.ac.jp

***Abstract* - We have been developing exoskeletons (exoskeletal robots) for assisting the motion of physically weak persons such as elderly persons or slightly disabled persons in daily life. In this paper, we propose a 3 DOF exoskeleton and its control system to assist the human upper-limb motion (shoulder joint motion and elbow joint motion) of physically weak persons. The proposed robot automatically assists the human motion mainly based on the skin surface electromyogram (EMG) signals. Fuzzy control has been applied to realize the sophisticated real-time control of the exoskeleton. Experiment has been performed to evaluate the proposed exoskeleton.**

I. INTRODUCTION

Many exoskeletons [1]-[4], which are sometimes called as power suits, man amplifiers, man magnifiers, or power assist systems, have been introduced for application in industry and military. Those exoskeletons are expected to augment human power. On the other hand, we have been developing exoskeletons (exoskeletal robots) [5]-[9] for assisting the motion of physically weak persons such as elderly persons or slightly disabled persons in daily life. Since our exoskeletons are supposed to generate flexible motion required in human living space, the motion assistance force is limited to be the same level as ordinal human force. In this paper, we propose a 3 DOF exoskeleton and its control system to assist the human upper-limb motion (shoulder flexion-extension motion, shoulder adduction-abduction motion, and elbow flexion-extension motion) of physically weak persons.

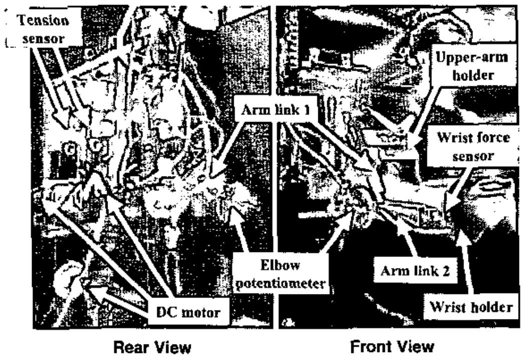
The electromyogram (EMG) signals of human muscles are important signals to understand how the human subject intends to move. The EMG signals can be used as input information for the robotic systems [10]-[12]. The proposed exoskeleton automatically assists the human motion mainly based on the skin surface EMG signals, since we can not expect the human subjects manipulate the exoskeleton by using any control equipment. Even though the EMG signals contain very important information, however, it is not very easy to predict the human upper-limb motion (elbow and shoulder motion) based on the EMG signals in a short time since many muscles are involved in the motion [13]-[16]. Furthermore, it is difficult to obtain the same EMG signals for the same motion even from the same human subject since the EMG signal is a biological signal which is affected by the physiological condition of the human subject. Therefore, the exoskeleton must be intelligent and flexible enough to deal with biological signals. In order to cope with this problem, fuzzy control has been applied to realize the sophisticated real-time control of the exoskeleton.

The fuzzy controller is supposed to control the elbow and shoulder joint angles of the exoskeleton based on the amount of the skin surface EMG signals of arm and shoulder muscles and the generated wrist force. Impedance characteristics of the elbow joint of the exoskeleton are also controlled by the controller. In the control rules, we consider the generated wrist force is more reliable when the subject activates the muscles little (when the EMG levels of the subject are low), and the EMG signals are more reliable when the subject activates the muscles a lot (when the EMG levels of the subject are high). In other words, the exoskeleton is controlled based on the generated wrist force when the EMG levels of the subject are low, and the exoskeleton is controlled based on the EMG signals when the EMG levels of the subject are high. The effect of the arm posture change is also taken into account in the controller [5][6]. By applying this control strategy, the exoskeleton supports the upper-limb motion in accordance with the human subject's intention. Experiment has been performed to evaluate the proposed exoskeleton and its control system.

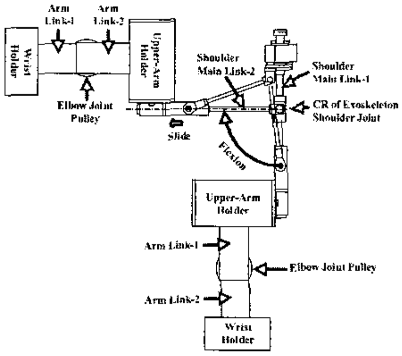
II. EXOSKELETON

The proposed exoskeleton (i.e., an exoskeletal robot) is supposed to be attached directly to the lateral side of a human subject. The architecture of the exoskeleton is shown in Fig. 1. The exoskeleton consists of four main links (two main links for shoulder joint motion and another two links for elbow joint motion), a frame, three DC motors, an upper-arm holder, a wrist holder, a wrist force sensor, driving wires, wire tension sensors, and driving motors. An air cushion is attached inside of the upper arm holder. By adjusting the air pressure of the air cushion, the upper arm holder can be properly attached to the upper-arm of any human subject. The shoulder flexion-extension and abduction-ad-

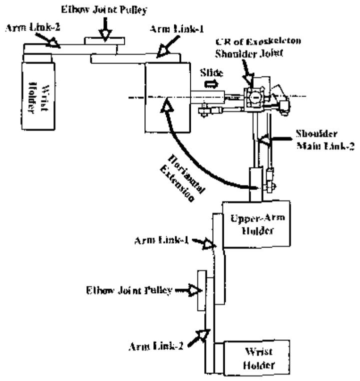
0-7803-7736-2/03/$17.00 ©2003 IEEE



(a) Attached exoskeleton



(b) Architecture (Side view)



(c) Architecture (Top view)

Fig. 1 The proposed exoskeleton

duction motions of the human subject (see Fig. 2) are assisted by the exoskeleton by activating the upper-arm holder, which is attached on the main link-2 for shoulder joint motion, using driving wires driven by two DC motors. The center of rotation (CR) of the shoulder joint is mechanically moved according to the shoulder joint angles in order to compensate for the difference between the location of the CR of the exoskeleton and that of the human subject [9]. The shoulder angle is measured by potentiometers attached to the links of the exoskeleton. The wire tension (driving force) is measured by the wire tension sensors.

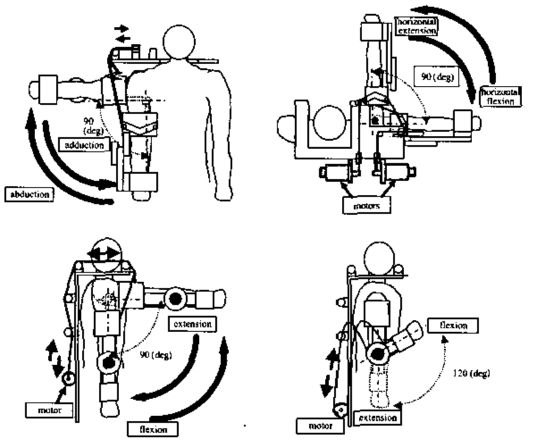


Fig. 2 Motion of the exoskeleton

The signals from the sensors are sampled at a rate of 1kHz (the EMG signals are also sampled at the same time) and low-pass filtered at 8Hz.

On the other hand, the elbow flexion-extension motion of the human subject (see Fig. 2) is assisted by the exoskeleton by activating the elbow joint pulley using the driving wire against the arm link-1 which is attached on the upper-arm holder. In order to make the movable links light weight, heavy DC motors are fixed on the frame.

Human elbow joint is mainly activated by biceps and triceps, and moves in 1 DOF. Human shoulder joint is activated by many muscles such as deltoid, pectoralis major, teres major, and trapezius, and moves in 3 DOF. In this study, EMG signals of biceps (lateral and proximal parts), triceps (lateral and proximal parts), deltoid (anterior, middle, and posterior parts), pectoralis major (lateral and clavicular parts), teres major, and trapezius (see Fig. 3) are measured and used for control of the proposed exoskeleton.

Usually, the limitation of the movable range of human elbow is between –5 and 145 degrees and the limitations of the movable range of human shoulder are 180 degrees in flexion, 60 degrees in extension, 180 degrees in abduction, and 75 degrees in adduction. Considering the practi-

Ch.1: Biceps (proximal part)
Ch.2: Biceps (lateral part)
Ch.3: Triceps (lateral part)
Ch.4: Triceps (proximal part)
Ch.5: Deltoid (anterior part)
Ch.6: Deltoid (posterior part)
Ch.7: Deltoid (middle part)
Ch.8: Pectoralis major
Ch.9: Teres major
Ch.10: Pectoralis major (clavicular part)
Ch.11: Trapezius

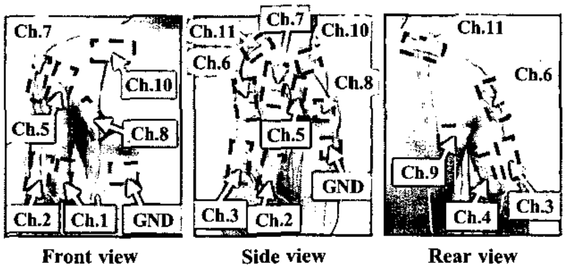


Fig. 3 Location of electrodes

cal application in everyday life and the safety of the human subject, the elbow joint motion of the proposed exoskeleton is limited between 0 and 120 degrees, and the limitation of the shoulder joint motion of the proposed exoskeleton are 0 degrees in extension and adduction, 90 degrees in flexion, and 90 degrees in abduction. The maximum angular velocity of the motor is limited by the hardware, as a safety measure. The maximum torque of the exoskeleton (i.e., the maximum current of the motor) is also limited by both the hardware and the software for safety. Furthermore, there is an emergency stop switch beside the exoskeleton.

III. CONTROL OF THE EXOSKELETON

Fuzzy control is applied to control the exoskeleton effectively and flexibly based on EMG signals which are affected by physiological condition of the human subject. The fuzzy IF-THEN control rules are designed based on the analyzed human subject's elbow and shoulder motion patterns in the pre-experiment. The EMG characteristics of human elbow and shoulder muscles studied in another research [13]-[16] are also taken into account. Since many muscles are involved in the upper-limb motion, it is not easy to make EMG-based control rules. Furthermore, since biceps and a part triceps are bi-articular muscles, the shoulder motion affects the amount of activity levels of these muscles. In the proposed control method, the definition of the antecedent part of the fuzzy IF-THEN control rules for elbow motion is adjusted based on the activation level of shoulder muscles. The effect of the arm posture change is also taken into account in the controller [5][6], since the arm posture change affects the amount of the EMG signals generated for the joint motion. In the proposed fuzzy controller, there are 16 rules (3 patterns) for elbow motion, 32 rules for shoulder motion, and 2 rules for controller switching between the EMG based control and the wrist force sensor based control. Consequently, 50 fuzzy IF-THEN control rules are prepared for control of the exoskeleton. The simplified proposed control architecture is depicted in Fig. 4.

In the proposed fuzzy control method, the exoskeleton is activated based on the generated wrist force signal when the EMG levels of the human subject's muscles are low. In this case, force control is carried out at the tip (at the position of the wrist) of the exoskeleton to assist the upper-limb motion of the human subject detected by the wrist force sensor. The desired wrist force in the force control is zero. The force control law is written as:

$$u_f = -K_f f \tag{1}$$

$$\tau_d = J_q^T u_f \tag{2}$$

where u_f is a force control command vector, K_f is a force control gain, f is the generated wrist force vector measured by the wrist force sensor, τ_d is a torque command vector for each joint, and J_q stands for the Jacobian matrix which relates the exoskelton's joint angular velocity to the Cartesian velocity. As the EMG levels of the human subject's muscles are increased (as the muscles of the human subject are activated), the wrist force signal is ignored and the EMG signals are utilized to activate the exoskeleton.

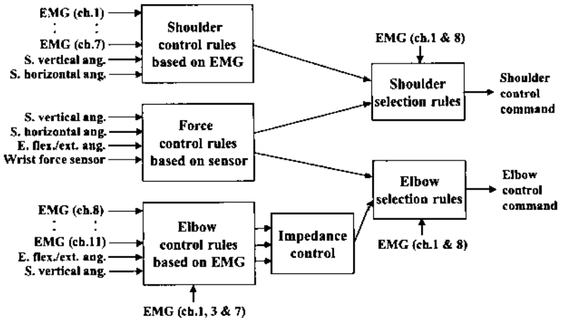


Fig. 4 Controller architecture

In order to extract the features from the raw EMG signals, the MAV (Mean Absolute Value) is calculated and used as input signals to the fuzzy controller. The equation of the MAV is written as:

$$MAV = \frac{1}{N}\sum_{k=1}^{N}|x_k| \tag{3}$$

where x_k is the voltage value at kth sampling, N is the number of samples in a segment. The number of samples is set to be 100 and the sampling time is set to be 1ms in this study.

The input variables of the fuzzy control are the MAV of EMG of eleven kinds of muscles, elbow angle, shoulder angles (vertical and horizontal angles), and force signals from the wrist force sensor. Four kinds of fuzzy linguistic variables (ZO: zero, PS: positive small, PM: positive medium, and PB: positive big) are prepared for the MAV of EMG (ch. 1, 3, and 7). Three kinds of fuzzy linguistic variables (ZO, PS, and PB) are prepared for the MAV of EMG (ch. 2, 4-6, and 8-11). Three kinds of fuzzy linguistic variables (EA: Extended, FA: Flexed, and IA: Intermediate angle) for elbow and shoulder angles.

The outputs of the fuzzy control are the torque command for shoulder motion [7], and the desired impedance parameters and the desired angle for elbow motion of the exoskeleton [8]. The torque command for the shoulder joint of the exoskeleton is then transferred to the force command for each driving wire. The relation between the torque command for the shoulder joint of the exoskeleton and the force command for driving wires is written as the following equation:

$$\tau_s = J_s^T f_{sd} \tag{4}$$

where τ_s is the torque command vector for the shoulder joint of the exoskeleton, f_{xd} is the force command vector for the driving wires, and J_s is the Jacobian which relates the exoskeletral robot joint velocity to the driving wire velocity. Force control is carried out to realize the desired

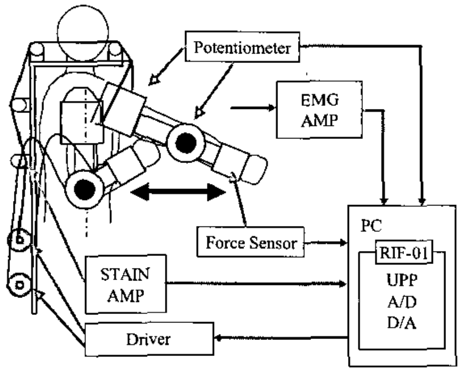


Fig. 5 Experimental setup

force (f_{sd}) in driving wires by the driving motors for shoulder motion of the exoskeleton.

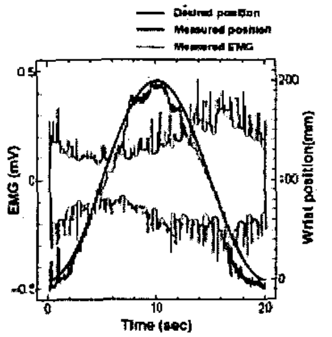
Impedance control is performed with the derived impedance parameters and the derived desired angle for the elbow joint control of the exoskeleton. The equation of impedance control is written as:

$$\tau_e = M_e(\ddot{q}_d - \ddot{q}) + B_e(\dot{q}_d - \dot{q}) + K_e(q_d - q) \qquad (5)$$

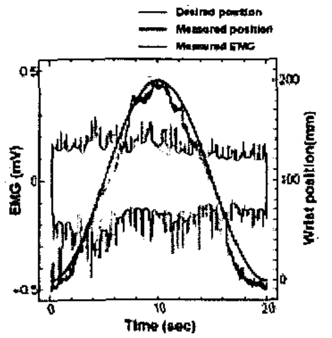
where τ_e denotes torque command for the elbow joint of the exoskeleton, M_e is the moment of inertia of the arm link-2 and human subject's forearm, B_e is the viscous coefficient generated by the fuzzy controller, K_e is the spring coefficient generated by the fuzzy controller, q_d is the desired joint angle generated by the fuzzy controller, and q is the measured elbow joint angle of the exoskeleton. The torque command for the elbow joint of the exoskeleton is then transferred to the torque command for the driving motor for the elbow motion of the exoskeleton.

IV. EXPERIMENT

Experiment has been carried out with a healthy human male subject (22 years old, 170cm, 53kg) to evaluate the effectiveness of the proposed exoskeleton. The experimental setup is shown in Fig. 5. In order to examine the effectiveness of the proposed exoskeleton in motion assist for both the elbow and shoulder joint of the human subject, three kinds of cooperative motions of the elbow and shoulder are performed in the experiment. In the motion-1 and motion-2, the human subject is supposed to move his wrist forward horizontally 200 [mm] from the initial position and backward again to the initial position following the target trajectory. In the motion-1, the initial position of the upper-limb is set to be 0 [deg] in both horizontal and vertical flexion angle of the shoulder joint, and 120 [deg] in flexion angle of the elbow joint. In the motion-2, the initial position of the upper-limb is set to be 0 [deg] in both horizontal and vertical flexion angle of the shoulder joint, and 90 [deg] in flexion angle of the elbow joint. The target wrist trajectory is 200sin(0.1πt) [mm] in the motion-1 and motion-2. In the motion-3, the human subject is supposed to draw a circle on the sagittal plane by his wrist. There is

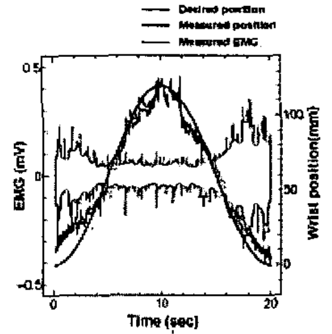


(a) proximal part of biceps (ch. 1)

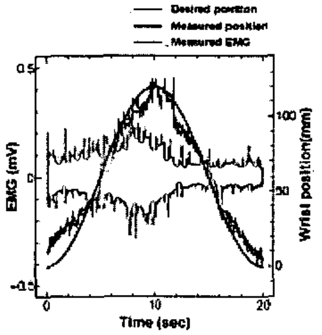


(b) anterior part of deltoid (ch. 5)

Fig. 6 Experimental results with the exoskeleton (Motion-1)

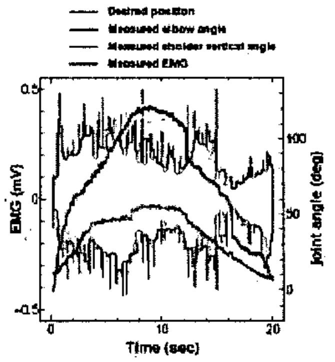


(a) proximal part of biceps (ch. 1)

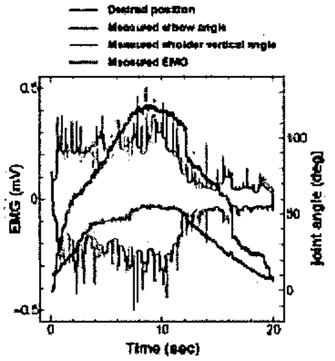


(b) anterior part of deltoid (ch. 5)

Fig. 7 Experimental results with the exoskeleton (Motion-2)

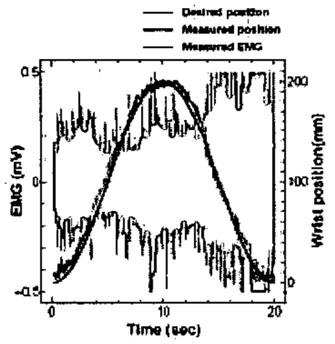


(a) proximal part of biceps (ch. 1)

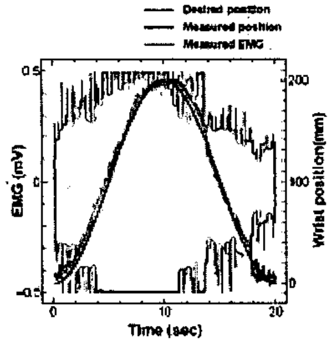


(b) anterior part of deltoid (ch. 5)

Fig. 8 Experimental results with the exoskeleton (Motion-3)

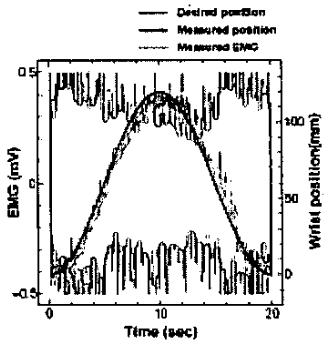


(a) proximal part of biceps (ch. 1)

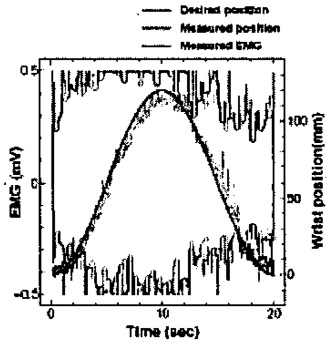


(b) anterior part of deltoid (ch. 5)

Fig. 9 Experimental results without the exoskeleton (Motion-1)

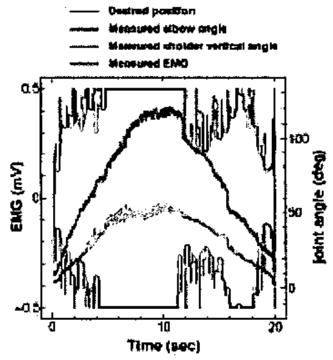


(a) proximal part of biceps (ch. 1)

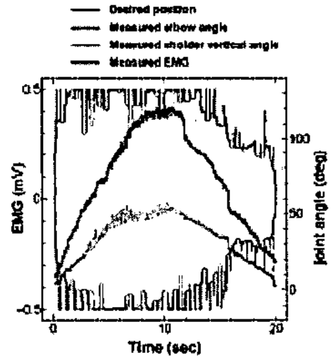


(b) anterior part of deltoid (ch. 5)

Fig. 10 Experimental results without the exoskeleton (Motion-2)



(a) proximal part of biceps (ch. 1)



(b) anterior part of deltoid (ch. 5)

Fig. 11 Experimental results without the exoskeleton (Motion-3)

no target trajectory in the motion-3.

All experiment is performed with and without the exoskeleton for comparison. If the proposed exoskeleton is effectively assisting the human motion, the activity levels of the EMG signals of the activated muscles are supposed to be reduced.

Figure 6, 7, and 8 show the experimental results of the motion-1, motion-2, and motion-3 with the assist of the exoskeleton, respectively. Figure 9, 10, and 11 show the experimental results of the motion-1, motion-2, and motion-3 without the assist of the exoskeleton, respectively. Only the results the EMG signals of ch. 1 (proximal part of biceps) and ch. 5 (anterior part of deltoid), which represent the elbow and shoulder muscles, are depicted here. From these experimental results, one can see that the activation levels of the EMG signals of the elbow and shoulder muscles were reduced when the human subject's motions were assisted by the exoskeleton. The well performed target trajectory following results prove that the exoskeleton was activated in accordance with the human subject's intention. These results show the effectiveness of the proposed exoskeleton in human upper-limb motion assist.

V. CONCLUSIONS

A 3 DOF exoskeleton and its control system were proposed to assist the human upper-limb motion of physically weak persons. Fuzzy control has been applied to realize the intelligent and flexible real-time control of the exoskeleton. Both elbow and shoulder joint motions of the human subject were automatically assisted by the proposed exoskeleton using the EMG signals of the human subject. Although the EMG based control of the upper-limb is complicated, the proposed controller realized the sophisticated cooperative motion support of the elbow and shoulder joints. The effectiveness of the exoskeleton and its control system was verified by experiment.

VI. ACKNOWLEDGMENT

The authors gratefully acknowledge the support provided for this research from Tateisi Science and Technology Foundation.

VII. REFERENCES

[1] J. M. Tressler, T. Clement, H. Kazerooni, M. Lim : "Dynamic Behavior of Pneumatic Systems for Lower Extremity Extenders", Proc. of 2002 IEEE International Conf. on Robotics and Automation, pp. 3248-3253, 2002.

[2] H. Kazerooni, S. L. Mahoney : "Dynamics and Control of Robotic Systems Worn by Humans", Trans. of the ASME, Journal of Dynamic Systems, Measurement, and Control, vol.113, no.3, pp.379-387, 1991.

[3] W. Cloud : "Man Amplifiers: Machines That Let You Carry a Ton", Popular Science, vol.187, no.5 pp.70-73&204, 1965.

[4] R.S. Mosher, B. Wendel : "Force-Reflecting Electrohydraulic Servomanipulator", Electro-Technology, pp.138-141, 1960.

[5] K. Kiguchi, K. Iwami, M. Yasuda, H. Kurata, K. Watanabe, T. Fukuda : "Intelligent Interface and adaptation of an Exoskeletal Robot for Human Shoulder Motion Support Considering Subject's Arm Posture", Proc. of IEEE International Conf. on Robotics and Automation, pp.3230-3235, 2002.

[6] K.Kiguchi, S.Kariya, T.Tanaka, K.Watanabe, T.Fukuda : "An Interface between an Exoskeletal Elbow Motion Assist Robot and a Human Upper-Arm", Journal of Robotics and Mechatronics, vol.14, no.5, pp.330-343, 2002.

[7] K. Kiguchi, K. Iwami, K. Watanabe, T. Fukuda : "A Study of an EMG-Based Exoskeletal Robot for Human Shoulder Motion Support", JSME International Journal, Series C, vol.44, no.4, pp.1133-1141, 2001.

[8] K. Kiguchi, S. Kariya, K. Watanabe, K. Izumi, T. Fukuda : "An Exoskeletal Robot for Human Elbow Motion Support – Sensor Fusion, Adaptation, and Control", IEEE Trans. on Systems, Man, and Cybernetics, Part B, vol.31, no.3, pp.353-361, 2001.

[9] K. Kiguchi, M. Yasuda, K. Iwami, K. Watanabe, T. Fukuda : "Design of an Exoskeletal Robot for Human Shoulder Motion Support Considering a Center of Rotation of the Shoulder Joint", Proc. of IEEE/RSJ International Conf. on Intelligent Robots and Systems (IROS'02), 2002. (to appear)

[10] K.A. Farry, I.D. Walker, R.G. Baraniuk : "Myoelectric Teleoperation of a Complex Robotic Hand", IEEE Trans. on Robotics and Automation, vol.12, no.5, pp.775-788, 1996.

[11] O. Fukuda, T. Tsuji, A. Ohtsuka, M. Kaneko : "EMG-based Human-Robot Interface for Rehabilitation Aid", Proc. of IEEE International Conf. on Robotics and Automation, pp.3942-3947, 1998.

[12] D. Nishikawa, W. Yu, H. Yokoi, Y. Kakazu : "EMG Prosthetic Hand Controller using Real-time Learning Method", Proc. of IEEE International Conf. on Systems, Man, and Cybernetics, pp.I-153-158, 1999.

[13] D.J. Bennett, J.M. Hollerbach, Y. Xu, I.W. Hunter : "Time-Varying Stiffness of Human Elbow Joint During Cyclic Voluntary Movement", Experimental Brain Research, vol.88, pp.433-442, 1992.

[14] R. Happee, F.C.T. Van der Helm : "The Control of Shoulder Muscles During Goal Directed Movements", An Inverse Dynamic Analysis, Journal of Biomechanics, vol.28, no.10, pp.1179-1191, 1995.

[15] B. Laursen, B.R. Jensen, G. Nemeth, G. Sjogaad : "A Model Predicting Individual Shoulder Muscle Forces Based on Relationship Between Electromyographic and 3D External Forces in Static Position", Journal of Biomechanics, vol.31, no.8, pp.731-739, 1998.

[16] A.T.C. Au, R.F. Kirsch : "EMG-Based Prediction of Shoulder and Elbow Kinematics in Able-Bodied and Spinal Cord Injured Individuals", IEEE Trans. on Rehabilitation Engineering, vol.8, no.4, pp.471-480, 2000.